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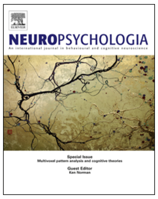

Synchronous activation within the default mode network correlates with perceived social support

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ABSTRACT

Perceived social support emphasizes subjective feeling of provisions offered by family, friends and significant others. In consideration of the great significance of perceived social support to health outcomes, attempt to reveal the neural substrates of perceived social support will facilitate its application in a series of mental disorders. Perceived social support potentially relies on healthy interpersonal relationships calling for cognitive processes like perspective taking, empathy and theory of mind. Interestingly, functional activations and connectivity within the default mode network (DMN) are extensively involved in these interpersonal skills. As a result, it is proposed that synchronous activities among brain regions within the DMN will correlate with self-report of perceived social support. In the present study, we tried to investigate the associations between coherence among the DMN regions and perceived social support at resting state. A total of 333 (145 men) participants were directed to fulfill the Multidimensional Scale of Perceived Social Support (MSPSS) after a 484-s functional magnetic resonance imaging (fMRI) scanning without any task. As a result, seed-based functional connectivity and power spectrum analyses revealed that heightened synchronicity among the DMN regions was associated with better performance on perceived social support. Moreover, results in the present study were independent of different methods, structural changes, and general cognitive performance.

1. Introduction

Across the long history of human development, human beings benefit to survive in complex social environments from broad social interactions (De Waal, 1982; Cheney & Seyfarth, 2007). Specifically, perceived social support from others can be regarded to reflect the social relations between self and others. Perceived social support puts emphasis on individuals' self-judgment on available social support (Zimet, Dahlem, Zimet, & Farley, 1988; Zimet, Powell, Farley, Werkman, & Berkoff, 1990). As a kind of social connections, perceived social support is proved to contribute to human health outcomes (Gulick, 1994; Helgeson & Cohen, 1996; Feldman, Downey, & Schaffer-Neitz, 1999; Peirce, Frone, Russell, Cooper, & Mudar, 2000). Moreover, relatively low level of perceived social support is associated with multiple mental disorders like loneliness (Solomon, Mikulincer, & Hobfoll, 1986; Jones & Moore, 1987; Cacioppo et al., 2006), anxiety and depression (Cohen & Wills, 1985; Zimet et al., 1988; Peirce et al., 2000; Mustafa, Nasir, & Yusooff, 2010; Hyde, Gorka, Manuck, & Hariri, 2011; Stice, Rohde, Gau, & Ochner, 2011).

As mentioned, the level of perceived social support depends on to what extent individuals are socially connected with others. Generally speaking, healthy social relations call for complex interpersonal skills like perspective taking, empathy and theory of mind. Interestingly, all the mentioned social skills rely on a robust pattern of intrinsic brain activity known as the default mode network (DMN) (for reviews see Schilbach, Eickhoff, Rotarska-Jagiela, Fink, & Vogeley (2008); Mars et al. (2012)). The default mode network, which is more activated during resting state than during goal-directed analyses of environmental stimuli (Shulman et al., 1997; Raichle et al., 2001), is demonstrated to be composed of regions along the anterior and posterior midline, the lateral parietal cortex (LP), prefrontal cortex (PFC), and the medial temporal lobe (Buckner, Andrews-Hanna, and Schacter, 2008). Generally speaking, regions within the default network tend to be activated in multiple cognitive processes like autobiographical memory, thinking about one's future, theory of mind and affective decision making (Ochsner et al., 2004; Buckner et al., 2008; Spreng, Mar, & Kim, 2009).

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In fact, numerous imaging studies confirm the critical role for the DMN in interpersonal skills of perspective taking, empathy and theory of mind. For example, brain regions recruited in adopting the perspective of others versus self-perspective are located at core regions of the DMN in medial prefrontal cortex (PFC) and posterior cingulate cortex (PCC) (Ruby & Decety, 2001, 2003, 2004). Moreover, imaging others in painful situation versus self in painful situation recruits most parts of the default network in PCC/precuneus and the right temporo-parietal junction (TPJ) as well as a cluster in the middle frontal gyrus (Jackson, Brunet, Meltzoff, & Decety, 2006). And empathy elicited by abstract visual information on the other's affective state engages brain areas strongly in precuneus, ventral medial prefrontal cortex (vmPFC), superior temporal cortex, and TPJ, which is suggested to infer and represent mental states of self and other (Lamm, Decety, & Singer, 2011). Besides, theory of mind can be regarded as the cognitive and regulatory component of empathy (Walter, 2012) generating activations in a large network including ventral- and dorsal medial prefrontal cortex (vmPFC and dmPFC), precuneus, TPJ, temporal poles (TP) and superior temporal sulcus (STS) (Frith & Frith, 2003; Gallagher & Frith, 2003; Walter et al., 2004; Frith & Frith, 2006a, 2006b; Carrington & Bailey, 2009). As a whole, extensive involvement of the DMN is revealed in interpersonal skills that are necessary to facilitate healthy social connections.

Generally speaking, recent years witness a rapid increase in studies revealing the critical role of resting-state functional connectivity (RSFC) within the DMN regions in social cognitions like autobiographical memory, empathy and theory of mind (Schilbach et al., 2008; Mars et al., 2012). Higher integration of the orbitofrontal cortex into the anterior DMN at rest is proved to correlate with higher pain ratings of visual stimuli depicting individuals in painful and non-painful situations (Otti et al., 2010). Moreover, functional connections between the TPJ and dmPFC are commonly detected in theory of mind and morality studies (for a review see Li, Mai, & Liu (2014)). In consideration of the extensive activations and connections of the DMN regions in these complex skills for social interactions, it is proposed that RSFC within the DMN regions will correlate with healthy social relations reflected possibly by high level of perceived social support. Moreover, because low-frequency oscillations are believed to contribute to functional connectivity (Cordes et al., 2001) and altered low-frequency oscillations in the DMN are revealed in mental disorders (Garrity et al., 2007), it's interesting to investigate whether low-frequency oscillations in the DMN correlate with self-report of perceived social support. Given the great significance of perceived social support to health outcomes (Gulick, 1994; Helgeson & Cohen, 1996; Feldman et al., 1999; Peirce et al., 2000), attempt to reveal the neural substrates of perceived social support will gain an understanding of these symptoms and may suggest new therapies for these disorders.

In the present study, synchronous activities within the DMN regions were investigated at rest to correlate with perceived social support. Seed-based functional connectivity was analyzed to inspect the synchronicity within the DMN regions. Moreover, synchronous activities within the default network were also assessed with the application of independent component analysis (ICA) to increase the robustness against method impact, followed by correlation analyses between self-report of social support and spectral power of the default component in different frequency bands. ICA was a model free data-driven approach which decomposed the data into independent component (Damaraju et al., 2010). The advantage of ICA over seed-based functional connectivity was that ICA did not require a predefined region of interest (McKeown et al., 1998; Damoiseaux et al., 2006; Kasparek et al., 2013). Besides, self-report of loneliness, general cognitive ability and DMN structure variances (Che et al., 2014) with regard to perceived social support were controlled as of the extensive involvement of the DMN regions in them (Damoiseaux et al., 2008; Cacioppo, Norris, Decety, Monteleone, & Nusbaum, 2009; Kanai, Bahrami, Roylance, & Rees, 2011; Powers, Wagner, Norris, & Heatherton, 2011; Cole, Yarkoni, Repovš, Anticevic, & Braver, 2012; Che et al., 2014Kanai et al., 2012). Taken together, we aimed at testing the hypothesis that coherence among the DMN regions was closely associated with perceived social support.

2. Methods

2.1. Subjects

Totally 350 right-handed, healthy volunteers participated in this study, of which 11 subjects were excluded for missing any question of the behavioral measures used and six participants were discarded owing to excessive head motions in the scanner. Finally, a total of 333 (145 men) subjects were included to the subsequent analyses. All the participants were undergraduate students of Southwest University. None had a history of neurological or psychiatric illness. The study was approved by Southwest University Brain Imaging Center Institutional Review Board at initial stage. According to the Declaration of Helsinki, all participants signed a written informed consent.

2.2. Assessment of perceived social support

The Multidimensional Scale of Perceived Social Support (MSPSS) was built to measure the level of subjective feeling of social support; it was tested to be a psychometrically sound measure of perceived social support (Zimet et al., 1988; Zimet et al., 1990). The MSPSS scale contained 12 items ranging from family, friend to significant other's support. Participants answered questions using a 7-point scale from “strongly disapproval” to “strongly approval”. Examples of the MSPSS items were as follows: “My family really tries to help me.” (Family support); “I have friends with whom I can share my joys and sorrows.” (Friend support); “There is a special person who is around when I am in need.” (Significant others support) (Zimet et al., 1988).

2.3. Assessment of general intelligence

The Raven's Progressive Matrices test was a good measure of the general factor of fluid intelligence (Raven, 1938). In previous studies, the Chinese version of the combined Raven's Progressive Matrices test (CCRPM) was testified to be a psychometrically sound measure of fluid intelligence (Li, Hu, Cheng & Jin, 1988; Wang & Qian, 1989; Wang, Di, & Qian, 2007). The CCRPM was composed of the Colored Progressive Matrices (A, B, and AB sets) and the last three parts of the Standard Progressive Matrices (C, D, and E sets), of which each set included five items with increasing difficulty. Numbers of corrected answers given in 40 min were counted as a measure of the CCRPM score.

2.4. Assessment of loneliness

The UCLA Loneliness Scale was a 20-items' questionnaire measuring one's general loneliness and degree of satisfaction with social relationships (Russell, 1996). Participants were instructed that each item described how people sometimes felt, and that they rated each item using a 4-point scale from “never” to “always”. An example statement was “How often do you feel that there is no one you can turn to?” After reverse scoring appropriate items, loneliness score was counted by summing the scores of all items ($\alpha = 0.88$).

2.5. Imaging data acquisition

Functional images were acquired in a 3.0-T Siemens Trio MRI scanner (Siemens Medical, Erlangen, Germany). The whole-brain resting-state functional images were obtained with the application of gradient-echo echo planar imaging (EPI) sequences with following parameters: slices=32, repetition time (TR) / echo time (TE)=2000 / 30 ms, flip angle=90°, field of view (FOV)=220 mm × 220 mm, and thickness / slice gap=3 / 4 mm.

2.6. Preprocessing

Preprocessing of the resting-state image data was performed with the application of the data processing assistant for resting state (DPARSF) software (http://www.restfmri.net/forum/DPARSF) (Yan et al., 2009). The toolbox worked on basis of SPM8 software package (Wellcome Trust Center for Neuroimaging, London, England). First 10 volumes of the functional images were discarded accounting for signal equilibrium and participants' adaptation to immediate environment. For the independent component analysis (ICA), the remaining 232 images were preprocessed including slice timing, head motion correction, spatial normalization and smoothing by using a 6-mm full-width-at-half-maximum Gaussian kernel. In the seed-based functional connectivity analysis, the smoothed data was subsequently linear detrended and filtered by a band pass filter (0.01–0.08 Hz). Also, in order to remove the potential impact of physiological artifacts, time series data for nine covariates (global signal, white matter, cerebrospinal fluid, and six motion parameters for head movement) were extracted and regressed out.

2.7. *Data analyses*

To determine the functional connectivity patterns of the DMN with regard to perceived social support, three regions of interest (ROIs) within the DMN were selected from the most significant foci in a metaanalysis of decreases during task performance (Shulman et al., 1997; Fox et al., 2005). Specifically, the seed regions were defined as spheres with a 6-mm radius centered in core regions of the DMN in the posterior cingulate cortex (−5, −49, 40), prefrontal cortex (−1, 47, −4) and the lateral parietal cortex (−45, −67, 36, Talairach coordinates) (Shulman et al., 1997; Fox et al., 2005). Analyses of functional connectivity were performed for the selected seed regions respectively. The average blood-oxygen-level-dependent (BOLD) signal time courses within each seed region were correlated to every voxel in the whole brain for each subject using Pearson's correlation coefficient. Then the correlation coefficients were converted to z-scores using the Fisher r-to-z transformation before group comparisons. To determine brain regions significantly correlated with the selected regions, we performed random effect one-sample *t*-tests of individuals' *z*-valued functional connectivity maps in a voxel-wise manner. In this way, composite functional connectivity maps were obtained for each ROI with a threshold of $p < 0.01$ (FWE (family-wise error) corrected; $T = 5.41$, df=340) and cluster size ≥ 270 mm^3 (10 adjacent voxels). Further, positive and negative functional connectivity maps of each ROI were saved as masks for subsequent analyses.

Multiple linear regression analyses were performed separately to identify brain regions with functional connectivity strength for the seed regions statistically correlated with the MSPSS scale scores with the application of the DMN maps created in the random effect one-sample *t*-tests, the multiple comparison corrections were performed at $p < 0.05$ using false discovery rate (FDR) approach, and the gender, age, general intelligence scores and structural variances in the post-PCC cluster (Che et al., 2014) were included as regressors of no interest.

Independent component analysis (ICA) was performed by using the “group ICA” function included in the fMRI toolbox (GIFT version 1.3 h; http://icatb.sourceforge.net) developed for the analysis of fMRI data (Calhoun, Adali, Pearlson, & Pekar, 2001; Calhoun, Liu, & Adalı, 2009; Schöpf, Windischberger, Kasess, Lanzenberger, & Moser, 2010). We took a two step data reduction approach using principal component analysis (PCA) to perform the ICA analysis. 60 principal components were obtained from each individual subject data in the first step. Then each of the subject's reduced data was concatenated in time and a second PCA was conducted to retain 50 components because high model order ICA enabled functional segmentation of the brain cortex (Kiviniemi et al., 2009; Abou-Elseoud et al., 2010; Allen et al., 2011). Next Infomax ICA algorithm was used to obtain 50 independent components. At last, time courses and spatial maps were computed for each subject in the stage of back reconstruction. The independent component spatial maps obtained were first z-scored and then entered into random effects analyses thresholded at $p = 0.01$ and corrected for family wise error (FWE) with a cluster extent threshold of 100 voxels. The default mode component was identified by correlating all components spatially with a default mode mask generated by WFU Pickatlas developed at Wake Forest Pharmaceuticals University (http://www.fmri.wfubmc.edu/) (Maldjian, Laurienti, Kraft, & Burdette, 2003). For the selected independent component that was identified as the default mode component, a mask was created for subsequent analyses.

We performed a power spectrum analysis on the smoothed data with the application of the REST toolkit (Song et al., 2011). Data was first detrended and then was combined into six equally spaced frequency bins between 0.01 and 0.24 Hz at 0.04 Hz intervals. For each frequency bin, the spectral power was first computed within the DMN mask created in the ICA analysis, and then correlated to the MSPSS scale scores by regressing out the gender, age, general intelligence scores and structural variances in the post-PCC cluster (Che et al., 2014).

2.8. *Supplementary analyses*

As of the role for DMN suppression in a series of mental disorders like schizophrenia (Meyer-Lindenberg et al., 2001; Whitfield-Gabrieli et al., 2009; Anticevic, Repovs, & Barch, 2011; Metzak et al., 2011; Nejad et al., 2011; Salgado-Pineda et al., 2011; Schneider et al., 2011; Dreher et al., 2012; Fatjó-Vilas et al., 2012) and depression (Sheline et al., 2009; Hamilton et al., 2011), it is interesting to know whether the anti-correlation between the DMN and the TPN (Task Positive Network) correlates with perceived social support. Composite functional connectivity maps obtained for each ROI in seed-based functional connectivity were used to create the DMN and the TPN masks. Then the ROI wise functional connectivity was applied to calculate the DMN–TPN anti-correlation with the covariates removed data with the DMN and the TPN masks as two ROIs (Song et al., 2011). Next, the *z*-valued functional connectivity between the DMN and the TPN were correlated with the MSPSS scale scores by ruling out the gender, age, general intelligence scores and structural variances in the post-parts of the PCC cluster (Che et al., 2014). Moreover, in order to investigate the correlations between perceived social support and functional connectivity within the TPN regions, seed-based functional connectivity was applied to inspect the TPN connectivity with three ROIs located in IPS (25, 57, 46), FEF (25, 13, 50) and MTG (45, 69, 2 Talairach coordinates) (Shulman et al., 1997; Fox et al., 2005). Subsequent analyses were as similar as what discussed before.

To rule out the effects of model order on ICA analysis, supplementary analyses were conducted by decomposing the smoothed data into 60 and 35 independent components respectively. Subsequent correlation analyses were carried out similar to that discussed before. Besides, spatial z-maps of the default component were used to link the DMN connectivity and perceived social support to increase the robustness of the results in whole-brain analyses corrected at $p < 0.05$ using FDR approach.

As collected later, only 278 (126 men) participants fulfilled the UCLA Loneliness Scale from the original sample. We first correlated the MSPSS scale scores with the UCLA Loneliness Scale scores and then replicated all the above analyses with loneliness as another regressor.

3. Results

3.1. *Sample descriptive*

All subjects had self-report of scores for the MSPSS scale (Mean ± SD: MSPSS = 64.25 ± 7.49), the CCRPM scale (Mean ± SD: CCRPM = 66.10 ± 3.49) and the UCLA Loneliness Scale (Mean ± SD: UCLA = 41.10 ± 7.66). The MSPSS scale scores did not correlate with age ($r = 0.02$, $p = 0.66$) and gender ($r = 0.09$, $p = 0.11$), but correlate with the CCRPM scores ($r = -0.19$, $p < 0.005$) and loneliness ($r = -0.36$, $p < 0.001$).

3.2. *Seed-based connectivity*

We examined brain areas that showed associations between the MSPSS scale scores, which reflected perceived availability of social support, and the strength of functional connectivity with the selected brain regions. For the seed PCC, a multiple regression analysis revealed that the MSPSS scale scores were statistically and positively correlated with the strength of functional connectivity between PCC and bilateral precuneus, bilateral ventral and dorsal medial prefrontal cortex and bilateral inferior parietal lobule extending to the lateral temporal cortex (see Table 1 and Fig. 1). For the seed LP, positive correlations were observed between the MSPSS scale scores and functional connectivity between LP and bilateral ventral medial prefrontal cortex, bilateral posterior cingulate cortex and bilateral inferior parietal lobule (see Table 2 and Fig. 1). For the seed PFC, the MSPSS scale scores were statistically correlated with the strength of functional connectivity between PFC and bilateral posterior cingulate cortex, bilateral inferior parietal lobule extending to the lateral temporal cortex (see Table 3 and Fig. 1). No negative correlation was observed.

3.3. *Power spectra*

As shown in Fig. 2, the component that correlated most significantly with the DMN template was selected as the default

Table 1
Brain regions with significant correlations between functional connectivity with PCC and the MSPSS scale scores.

Region	MNI coordinates			Cluster size	*T*-score
	X	*Y*	*Z*		
R/L precuneus	0	−45	36	1054	5.81
R/L medial prefrontal cortex	6	48	−18	666	5.60
L inferior parietal lobule	−51	−66	30	202	4.70
R inferior parietal lobule	48	−63	39	97	4.06

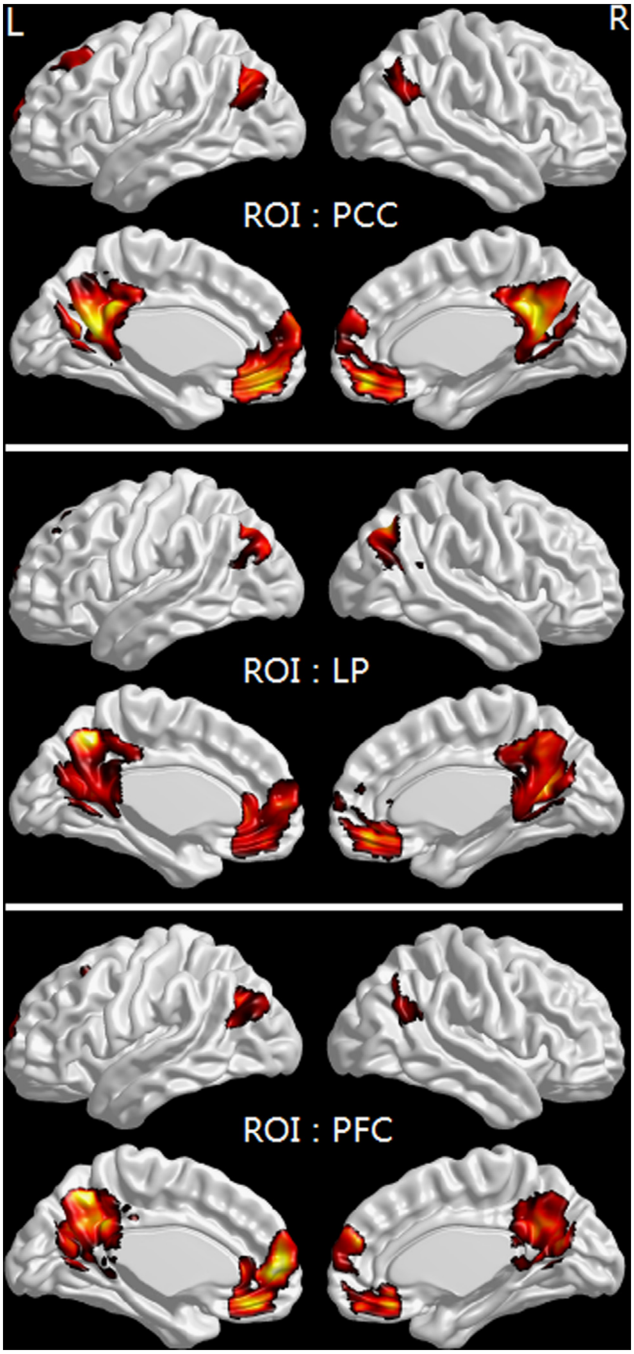

Fig. 1. The MSPSS scale scores were statistically correlated with the strength of functional connectivity within the DMN regions regressing out gender, age, general intelligence scores, loneliness and structural variances in the post-PCC cluster when the seed regions were centered in PCC, LP and PFC respectively.

Table 2
Brain regions with significant correlations between functional connectivity with LP and the MSPSS scale scores.

Region	MNI coordinates			Cluster size	*T*-score
	X	*Y*	*Z*		
R/L posterior cingulate cortex	−6	−54	45	1036	5.86
R/L ventral medial prefrontal cortex	6	45	−9	494	5.17
L inferior parietal lobule	−36	−69	42	124	4.20
R inferior parietal lobule	39	−66	42	140	4.17

Table 3
Brain regions with significant correlations between functional connectivity with PFC and the MSPSS scale scores.

Region	MNI coordinates			Cluster size	*T*-score
	X	*Y*	*Z*		
R/L posterior cingulate cortex	−6	−54	45	505	5.40
R/L medial prefrontal cortex	−3	54	3	305	5.46
L inferior parietal lobule	−51	−69	33	16	3.90
R inferior parietal lobule	48	−66	45	15	3.80

mode component (Mean=0.55, SD=0.02). Results showed that spectral power within the DMN mask in the two low-frequency bands (0.01–0.08 Hz) correlated positively with the MSPSS scale scores regressing out the gender, age, general intelligence scores and structural variances in the post-PCC cluster. However, significant correlation in high frequency bands was not observed (0.08–0.24 Hz) (Fig. 3).

3.4. Supplementary results

Results showed that the anti-correlation between the DMN and the TPN was not related to the self-report of perceived social support across different composite functional connectivity maps obtained for each ROI (seed PCC: $r=-0.16$, $p=0.77$; seed LP: $r=0.03$, $p=0.58$; seed PFC: $r=0.01$, $p=0.88$). Moreover, perceived social support was not correlated with TPN connectivity across three different ROIs.

Increased (60) and decreased (35) independent components revealed results similar to that observed in 50 independent components. Statistical correlations between spectral power within the DMN mask and perceived social support were observed only in the two low-frequency bands (0.01–0.08 Hz) (see Figs. 1 and 2 in Supplementary materials).

Besides, perceived social support linked with DMN connectivity in left precuneus, bilateral mPFC and right lateral temporal cortex, namely main areas of the DMN, with the application of spatial z-maps of the default component (see Fig. 3 in Supplementary materials).

In spite of the negative correlation observed between perceived social support and loneliness, seed-based functional connectivity and ICA analyses revealed similar patterns of intrinsic connectivity within the DMN after regressing out the UCLA Loneliness Scale scores to those did not (see Tables 1–3 and Fig. 1).

4. Discussion

The aim of the present study was to reveal the associations between synchronicity within the default mode network and perceived social support. Results supported the hypothesis by showing that heightened coherence among the DMN regions contributed to relatively better performance on perceived social support. Specifically, enhanced functional connections between several hubs of the DMN, such as PCC, precuneus, IPL and PFC, were observed in individuals scoring high in the MSPSS. Moreover, high scorers in the MSPSS scale showed heightened low-frequency oscillations (0.01–0.08 Hz) within the DMN, which were interpreted as increased synchronicity between brain regions involved in the default mode network (Garrity et al., 2007; Cauda et al., 2009). These results were specific by ruling out the gender, age, loneliness, general intelligence scores and structural variances in the post-PCC cluster and robust by factoring the effects of model order (see Figs. 1 and 2 in Supplementary materials) and data sources in ICA analysis (see Fig. 3 in Supplementary materials).

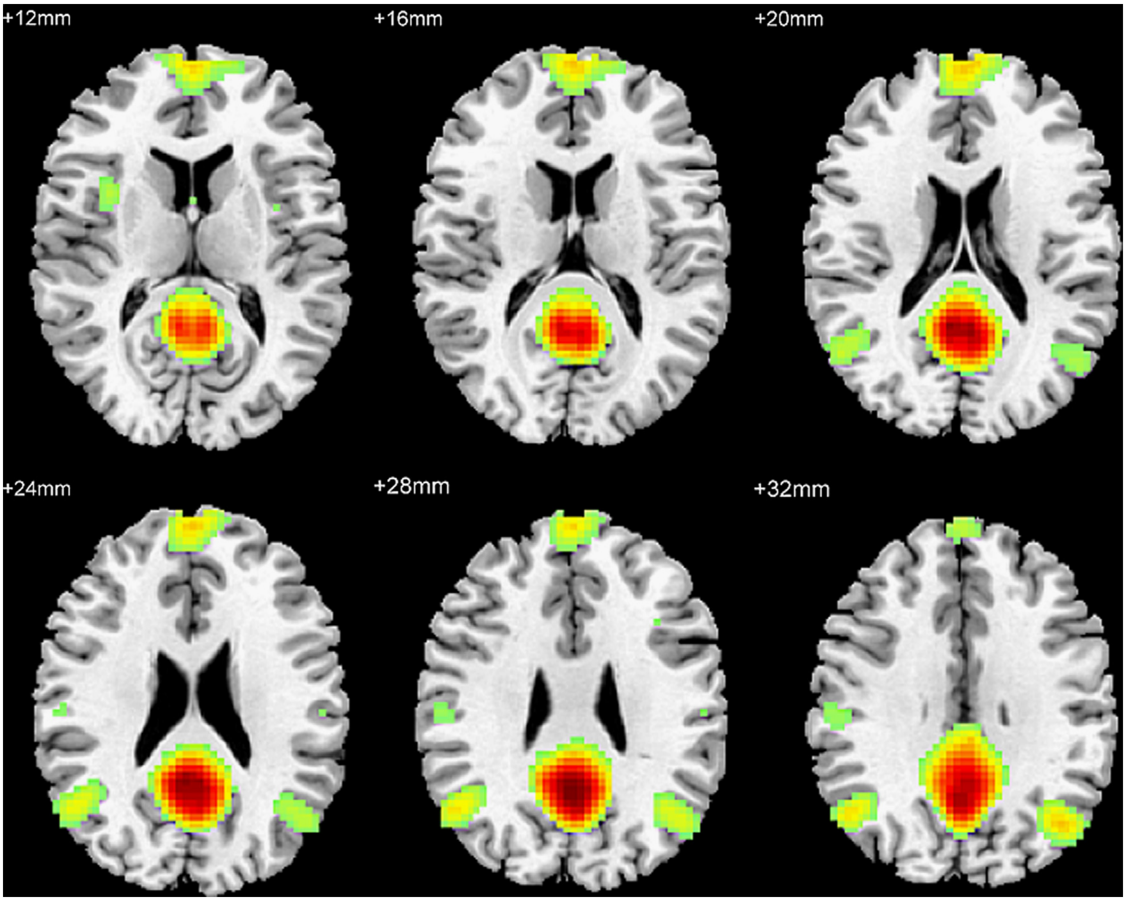

Fig. 2. Default mode component was identified in the independent component analysis.

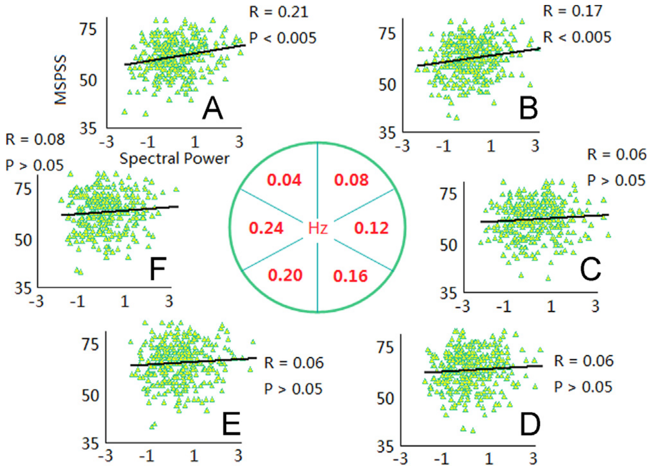

Fig. 3. Scatter diagrams showed the correlations between spectral power of different frequency bands within the DMN mask and the MSPSS scale scores. (A)–(F) meant the six frequency bins between 0.01 and 0.24 Hz at 0.04 Hz intervals respectively. Of note, the horizontal axes represented the standardized residual of spectral power regressing out gender, age, general intelligence scores and structural variances in the post-PCC cluster. Statistical correlations between spectral power within the DMN mask and the MSPSS scale scores were observed only in the two low frequency bands (0.01–0.08 Hz).

As discussed, accumulating evidences support the proposal that social cognitions like perspective taking, empathy and theory of mind recruit extensive regions within the default mode network. Frontal damage leads to impaired perspective-taking ability (Price, Daffner, Stowe, & Mesulam, 1990) and cognitive flexibility (Eslinger, 1998). Moreover, self-awareness and agency are argued to share neural representations, of which right inferior parietal cortex and the prefrontal cortex play a special role in interpersonal awareness (Decety & Sommerville, 2003). Besides, theory of mind is considered as the cognitive component of empathy (Walter 2012) recruiting a large-scale network similar to the DMN (Frith & Frith, 2003; Gallagher & Frith, 2003; Walter et al., 2004; Frith & Frith, 2006a, 2006b; Carrington & Bailey, 2009). When it comes to the perspective of functional coupling, recent studies reveal the significance of functional connectivity between the DMN regions in these interpersonal interactions (Li et al., 2014; Otti et al., 2010). As a result, heightened functional connectivity between the DMN regions in the present study may facilitate the implementations of perspective taking, empathy and theory of mind, leading to better performance in social interactions and perceived social support.

Correlations between perceived social support and functional coupling within the DMN regions can be enlightened with regard to the role of DMN regions in healthy social connections and prosocial behavior. In fact, a series of studies confirm the involvement of DMN regions in healthy social connections and prosocial behavior. A structural MRI (magnetic resonance imaging) study observes a negative correlation between loneliness and gray matter volume in the left posterior superior temporal sulcus, implying the critical role of STS in perception of social stimuli (Kanai et al., 2012). And gray matter volume of the middle temporal gyrus and posterior PCC correlate with online social network size (Kanai et al., 2011) and perceived social support respectively (Che et al., 2014). Moreover, neural regions involved in processing social connection or social support are detected in vmPFC and PCC (Younger, Aron, Parke, Chatterjee, & Mackey, 2010; Eisenberger et al., 2011; Eisenberger, 2013a, 2013b). Besides, to investigate the neural conditions of prosocial thoughts and behavior, researchers show that activations in the mPFC recruited by social exclusion and empathy can predict prosocial thoughts and behavior (Mathur, Harada, Lipke, & Chiao, 2010; Masten, Morelli, & Eisenberger, 2011). As a result, increased functional connectivity within the DMN regions in participants may suggest sound social connections and relatively strong intention to help others, linking to high level of perceived social support.

As is shown in seed-based functional connectivity, key components of the default network are involved in the self-report of available social support by functionally linking with each other. Furthermore, another piece of evidence supports this argument with the examination of the low-frequency fluctuations of the default network. As expected, low-frequency oscillations (0.01–0.08 Hz) of the DMN positively correlate with perceived social support (Fig. 3). Generally speaking, low-frequency fluctuations contribute to temporal synchronicity or functional connectivity among functionally related regions of the brain (Cordes et al., 2001; Garrity et al., 2007; Cauda et al., 2009; Malinen et al., 2010). As a result, heightened low-frequency oscillations observed in high scorers of the MSPSS scale can be interpreted as enhanced temporal coherence among brain areas of the DMN. In consideration of the extensive functional activations and connectivity of the DMN regions in interpersonal social interactions, it is reasonable to assume that high level of perceived social support is correlated with low-frequency oscillations of the DMN. Moreover, it is interesting to find that low-frequency oscillations of the DMN are associated with perceived social support with regard to altered low-frequency fluctuations in mental disorders like schizophrenia (Garrity et al., 2007) and the role of perceived social support in a series of mental disorders.

In consideration of the multiple relations among perceived social support, loneliness and functional activations and connectivity within the DMN regions, it is rational to take loneliness into account with regard to the observed correlation between perceived social support and simultaneous activities within the DMN regions. In fact, loneliness is demonstrated to link with perceived social support in a few studies (Solomon et al., 1986; Jones & Moore, 1987; Cacioppo et al., 2006). Moreover, altered structural variances, functional activations and coupling within the DMN regions are repeatedly revealed in lonely individuals (Cacioppo et al., 2009; Kanai et al., 2011; Powers et al., 2011; Kanai et al., 2012) and autism spectrum disorders (ASD) (Frith, 2001; Cherkassky, Kana, Keller, & Just, 2006; Kennedy, Redcay, & Courchesne, 2006; Kennedy & Courchesne, 2008; Schulte-Rüther et al., 2011; Lynch et al., 2013). In line with previous studies, perceived social support negatively correlates with loneliness in the present study. However, correlations between perceived social support and intrinsic connectivity within the default network are independent of loneliness in main results by ruling out the UCLA Loneliness Scale scores (Fig. 1). As a result, it is suggested that heightened synchronous activities within the DMN regions may facilitate to interpersonal social interactions, leading to high level of perceived social support and decreased self-report of loneliness in consideration of the defects of lonely individuals in interpersonal skills (Cacioppo et al., 2009; Kanai et al., 2011; Powers et al., 2011; Kanai et al., 2012).

Recently, attentions paid to the role of the DMN suppression in cognition and mental diseases increase. DMN suppression is proved to support a series of goal-directed cognitive processes (for a review see Anticevic et al. (2012)). For instance, the DMN–FPCN (fronto-parietal control network) relationship is predictive of intelligence (Cole et al., 2012). Moreover, lack of DMN suppression is observed in several mental illness such as schizophrenia (Whitfield-Gabrieli et al., 2009; Anticevic et al., 2011; Metzak et al., 2011; Nejad et al., 2011; Dreher et al., 2012; Fatjó-Vilas et al., 2012) and depression (Sheline et al., 2009; Hamilton et al., 2011). In the present study, however, functional coupling within the TPN regions and the anti-correlation between the DMN and the TPN are not capable of predicting the self-report of perceived social support in spite of the associations between perceived social support and mental disorders. Anyway, it is interesting for future researchers to investigate these relationships by designing protocols that can represent the perceived social support.

To the best of our knowledge, this is the first study to reveal that synchronicity within the DMN regions contributes to self-report of available social support at resting state. Moreover, our main findings are independent of different methods, structural changes, and general cognitive performance. However, there are few limitations that attention should be paid to in this study. For example, we failed to administrate any measure of memory, so it is difficult to rule out the possible effects of memory on reported results as of the role of DMN activation in social working memory (Meyer & Lieberman, 2012; Meyer, Spunt, Berkman, Taylor, & Lieberman, 2012) and the proposed part of memory in empathy (Beadle, Tranel, Cohen, & Duff, 2013) and prosocial behavior (Gaesser, 2012). As a result, it is reasonable to investigate the impacts of memory on the relations between perceived social support and DMN activations and connectivity in future studies. Moreover, new methods can be applied to construct an overall connectivity of regions within the DMN and examine individual differences in low fluctuation rates. This speaks to interpretation – is it truly the connectivity between DMN regions which counts, or is it just that participants use their DMNs differently – at least in a less variable way.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2014.07.035.

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